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Oxygen isotope record of magmatic evolution of alkaline volcanic rocks at The Pleiades, northern Victoria Land, Antarctica

Nak Kyu Kim[1]*, Mi Jung Lee[1], Jong Ik Lee[1], and Jihyuk Kim[2]

[1]Division of Earth Sciences, Korea Polar Research Institute, Incheon 21990, Republic of Korea
[2]School of Earth and Environmental Sciences, Seoul National University, Seoul 08826, Republic of Korea

ABSTRACT: Oxygen isotopes are used to examine the well-documented magmatic evolution of alkaline volcanic rocks at The Pleiades in northern Victoria Land (NVL), Antarctica. Oxygen isotopes were measured in olivine, clinopyroxene, and plagioclase phenocrysts to better understand the origin and evolution of the sodic and potassic differentiation lineages. The volcanic rocks at The Pleiades evolved from a parental basanite by fractional crystallization in crustal magma chambers. Olivine which crystallizes first in the mafic magmas provides the initial oxygen isotope composition of the magmatic lineages. The $\delta^{18}O_{OL}$ values for the mafic lavas in the sodic lineage are lower than the potassic lineage. The primary melt derived from the metasomatized lithospheric mantle may have consumed a low-$\delta^{18}O$ amphibole metasome. Subsequently, the melt would have evolved to the normal-$\delta^{18}O$ potassic lineage magma by a large contribution from surrounding peridotite. In contrast, the sodic lineage magma might preserve low-$\delta^{18}O$ characteristics because of insufficient reaction with the surrounding mantle peridotite. Intermediate rocks of the potassic lineage exhibit a wide variation in their oxygen isotope compositions and it deviates from the theoretical normal-$\delta^{18}O$ trend. Hence, variable $\delta^{18}O_{OL}$ values of the intermediate rocks suggest that high-$\delta^{18}O$ recorded in olivine could be reconciled with an assimilation of crustal rocks in NVL, and hydrothermally altered material may have contributed to low-$\delta^{18}O$ signature of the olivines.

Key words: The Pleiades volcanic complex, McMurdo Volcanic Group, Antarctica, oxygen isotope, AFC process

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1. INTRODUCTION

The oxygen isotope system can be used to diagnose mantle heterogeneity and crust-mantle interaction (Woodhead et al., 1993; Eiler, 2001; Cooper et al., 2004; Bindeman, 2008; Nardini et al., 2009). Variable oxygen isotope data can be used to constrain the compositions of magma sources and reflect the magmatic evolution of volcanic rocks. Both of mid-ocean ridge basalt (MORB) and oceanic island basalt (OIB) are types of mantle-derived rocks that are formed through partial melting of the mantle having fairly homogeneous oxygen isotope composition (Zindler and Hart, 1986; Ito et al., 1987; Eiler et al., 2000b; Cooper et al., 2004). The end-members of OIB, consisting of a depleted MORB mantle component (DMM), enriched mantle components 1 and 2 (EM 1 and EM 2), and a high U/Pb mantle component (HIMU), result from intraplate volcanism and are classified based on their radiogenic isotopic characteristics (Zindler and Hart, 1986). In equilibrium condition, $\delta^{18}O$ values of the volcanic rocks increase about 1‰ by the effect of fractional crystallization process (Woodhead et al., 1987; Harris et al., 2000; Eiler, 2001; Bucholz et al., 2017). Oxygen isotope studies have suggested that such mantle components were affected by recycled crustal materials (Woodhead et al., 1993; Harmon and Hoefs, 1995; Eiler, 2001; Byerly et al., 2017). Studies for suit of volcanic rocks, however, have shown that $\delta^{18}O$ values of the rocks distinct from the normal-$\delta^{18}O$ array expected by experimental modelling and measurement of natural sample (Eiler et al., 2000a; Widom and Farquhar, 2003; Bindeman et al., 2004; Iovine et al., 2018; Troch et al., 2020). Oxygen isotopes can

***Corresponding author:**
Nak Kyu Kim
Division of Earth Sciences, Korea Polar Research Institute, Incheon 21990, Republic of Korea
Tel: +82-32-760-5447, Fax: +82-32-760-5497, E-mail: kimnk@kopri.re.kr

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be highly fractionated in igneous rocks, because of water-rock interactions at variable temperature conditions (Gregory and Taylor, 1981; Alt et al., 1986). Particularly, low-$\delta^{18}O$ meteoric water producing in high latitudes can change the $\delta^{18}O$ values of volcanic rocks when it has undergone hydrothermally alteration (Sharp et al., 2018). The low-$\delta^{18}O$ volcanic rocks also reflect the interaction of magma with hydrothermally altered materials (Harmon and Hoefs, 1995; Eiler et al., 2000a) Therefore, the oxygen isotope anomaly has an information on contribution of crustal contamination during magma evolution (Taylor, 1980; DePaolo, 1981).

The U-Pb ages of detrital zircons and Re-depletion ages of mantle sulfides in northern Victoria Land (NVL), Antarctica, indicate information on multiple intensive magmatic events (Melchiorre et al., 2011; Estrada et al., 2016). Both simultaneous and comprehensive age records suggest that the NVL lithosphere, including the felsic crust and lithospheric mantle has experienced an extensive history of magmatic evolution from the Archean to Phanerozoic. The Pleiades is a young alkaline volcanic complex that is included in the Cenozoic McMurdo Volcanic Group, which formed in an intraplate tectonic setting of NVL, Antarctica (Kyle, 1990; Kim et al., 2019a). The volcanic rocks of The Pleiades consist of a sodic and a potassic fractionation lineages (Kyle, 1982). Kim et al. (2019a) suggested that the primary magmas of both lineages were derived from a hydrous mineral bearing metasomatized lithospheric mantle with a HIMU-like isotopic signature, as well as Nb-enrichment and K-depletion when compared with primitive mantle compositions. After the partial melting of the lithospheric mantle, the parental basanites for the potassic lineage could have been formed through a high degree of assimilation or reaction with the surrounding anhydrous mantle peridotite, while the sodic magma assimilated less of this surrounding peridotite (Kim et al., 2019a). In this study we present new oxygen isotope data for minerals separated from the volcanic rocks of The Pleiades. The data provide insights into the role of hydrothermally altered materials in magmatic evolution of the volcanic rocks.

2. SAMPLE LOCATION AND ANALYTICAL PROCEDURES

NVL is part of East Antarctica and is bounded to the east by the Transantarctic Mountains (TAM) (Fig. 1a). NVL is an amalgamation of the Wilson, Bowers, and Robertson terranes at the Paleo-Pacific continental margin, which was formed by ancient subduction processes and ultra-high pressure (UHP) metamorphism during the Ross orogeny (Fig. 1b) (Rocchi et al., 2011; Goodge et al., 2012; Di Vincenzo et al., 2016). Eclogite as nodules enveloped in the gneiss complex of the Lanterman Range located on the border between the Bowers and Wilson terranes is evidence of the UHP metamorphism experienced by this margin (Fig. 1b) (Di Vincenzo et al., 2016; Kim et al., 2019c). The Pleiades volcanic complex is composed of a series of young (< 1 Ma) cones and domes erupted on the top of the TAM (Kyle, 1982; Kim et al., 2019a). It is situated above rocks of the Bowers Terrane (72.6–72.8°S, 165.4–165.7°W, Fig. 1b). The volcanic rocks of The Pleiades are alkaline in composition and the parental magmas were formed

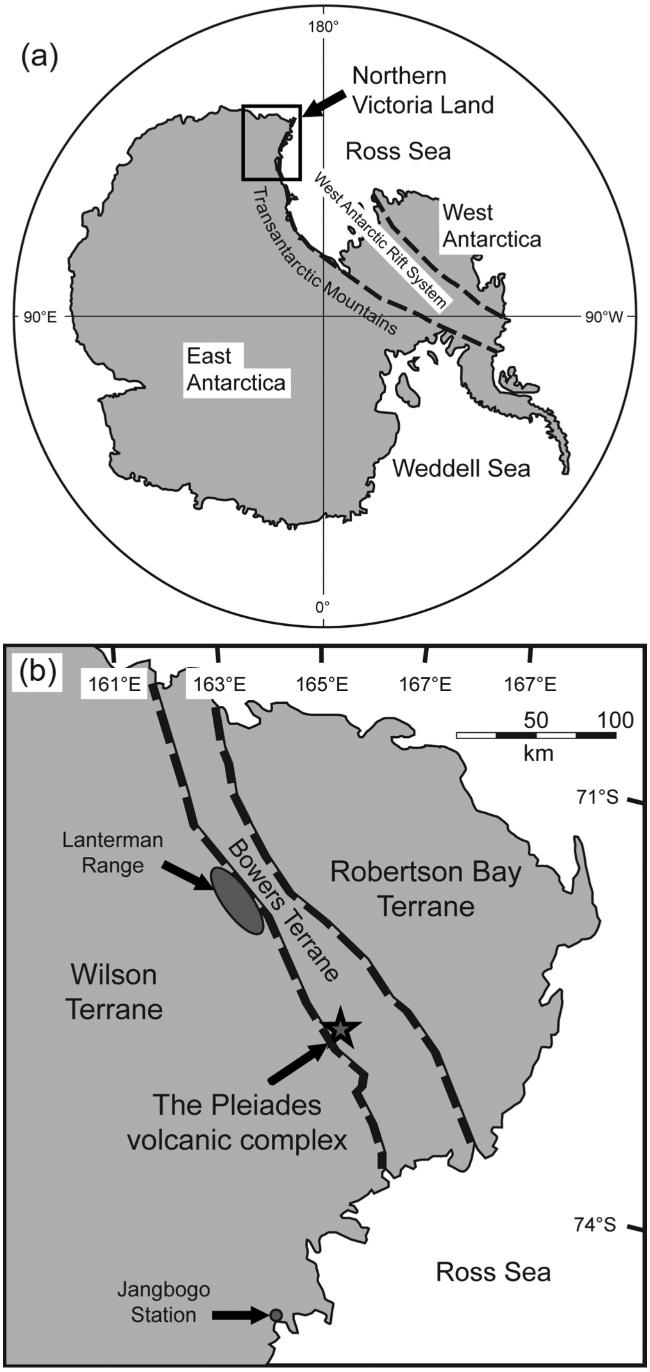

Fig. 1. (a) Map of Antarctica displaying the location of northern Victoria Land (NVL). (b) Location of The Pleiades volcanic complex marked with a star symbol.

by partial melting of the lithospheric mantle. Magmatism was triggered by the upwelling of asthenospheric mantle associated with the West Antarctic Rift System (Rocchi et al., 2002; Coltorti et al., 2004; Nardini et al., 2009; Perinelli et al., 2011; Pelorosso et al., 2016; Panter et al., 2018; Day et al., 2019; Kim et al., 2019a). Studies on mantle xenoliths erupted in alkaline basalts in this region suggest that the amphibole-bearing lithospheric mantle beneath NVL was affected by varying degrees of metasomatism (Perinelli et al., 2006, 2011). The geochemical and isotopic data from alkaline magmatism also indicate that the source mantle of the Cenozoic NVL basalts was metasomatized to produce amphibole-rich veins (Panter et al., 2006; Nardini et al., 2009).

Oxygen isotopes were measured in olivine, clinopyroxene, and plagioclase separated from sample of The Pleiades volcanic rocks. We also measured oxygen isotopes in whole rock granodiorite, migmatite, and Granite Harbour Intrusive Complex (GHIC) samples. These are regarded as the basement rock of NVL and potential contaminants and they are described in detail by Kim et al. (2019a). We also analyzed an eclogite sample which is collected from the Lanterman Range. The volcanic rocks of The Pleiades define the potassic and sodic evolutionary lineages (Kyle, 1982; Kim et al., 2019a). Mafic to felsic lavas of the potassic lineage have larger phenocrysts than those of the sodic lineage. Olivine, clinopyroxene, and plagioclase were separated from seven samples of the potassic lineage and two samples of the sodic lineage. Samples were crushed using a jaw-crusher and tungsten carbide mortar and then sieved to obtain a fine size fraction of 200–700 μm. Magnetic minerals were removed using a hand-magnet. The crushed samples were washed with filtered water in an ultrasonic bath and leached in 3N HCl for 30 min at room temperature to remove any surface contaminants. After rinsing and overnight drying, the minerals were hand-picked under a binocular microscope. The whole-rock oxygen isotope compositions of the basement rocks were determined using a sample fraction after the crushing, sieving, and washing steps. Oxygen isotope analysis was conducted at the Korea Polar Research Institute (KOPRI) using a laser fluorination system (Kim et al., 2019b). Aliquots of approximately 2 mg were heated using a 25W CO_2-laser in a BrF_5 atmosphere. After fluorination, the liberated oxygen was purified in a series of steps. The oxygen isotope composition was analyzed using a dual-inlet mass spectrometer (MAT 253 plus, Thermo Fisher Scientific). Oxygen isotope compositions are reported relative to the VSMOW (Vienna Standard Mean Ocean Water) scale in δ-notation, with $\delta^{18}O$ (‰) = $[(^{18}O/^{16}O)_{sample}/(^{18}O/^{16}O)_{VSMOW}] - 1$. We calibrated the working standard O_2 gas by direct measurement of VSMOW in an identical purification line. We also measured the SLAP (Standard Light Antarctic Precipitation) and applied the VSMOW-SLAP scaling to reduce inter-laboratory differences (Gonfiantini, 1978). The measured $\delta^{18}O$ value of SLAP relative to VSMOW was −54.48 ± 0.15‰ (n = 8, 1σ), which was normalized to −55.50‰ to obtain the scaling factor. Based on the results of standard water analysis, we normalized our data by applying scaling factor of 1.019 and the VSMOW-SLAP scaling method (Kusakabe and Matsuhisa, 2008).

3. RESULTS

3.1. Oxygen Isotope Composition

Oxygen isotope analyses of minerals from The Pleiades volcanic rocks and whole rock analyses of NVL basement rocks are given in Table 1. $\delta^{18}O$ in 8 olivine samples range from 4.21‰ to 5.36‰, in 8 clinopyroxene samples it is 5.13‰ to 5.87‰ and and 7 plagioclase samples have $\delta^{18}O$ values ranging from 6.48‰ to 7.03‰. Clinopyroxene and plagioclase have a smaller oxygen isotope range than the olivine. The averaged $\delta^{18}O$ values for olivine (= $\delta^{18}O_{OL}$), clinopyroxene (= $\delta^{18}O_{CPX}$), and plagioclase (= $\delta^{18}O_{PL}$) in the mafic rocks (samples K16012708-4, J14120107-1, and J14120503-2) are 5.00 ± 0.20‰, 5.18 ± 0.06‰, and 6.54‰ respectively. The $\delta^{18}O_{OL}$ and $\delta^{18}O_{CPX}$ values are lower than normal mantle values of 5.18 ± 0.14‰ for $\delta^{18}O_{OL}$ and 5.57 ± 0.16‰ for $\delta^{18}O_{CPX}$ (Mattey et al., 1994). On a plot of $\delta^{18}O_{CPX}$ versus $\delta^{18}O_{OL}$, only 3 samples plot with realistic temperature and 4 samples plot at a significant distance from the equilibrium fractionation line (Fig. 2a). $\delta^{18}O$ values of the basement rocks that include granodiorite, migmatite, and GHIC range from 6.39‰ to 14.82‰. This range is significantly larger than that measured in the constituent minerals of The Pleiades. Measured $\delta^{18}O$ in the eclogite is 10.23‰ (Table 1).

Based on theoretical calculations, the $\delta^{18}O$ values of phenocrysts in mafic rocks can be ranked as follows: $\delta^{18}O_{OL} < \delta^{18}O_{CPX} < \delta^{18}O_{PL}$ (Zhao and Zheng, 2003). At high temperatures, oxygen isotopic fractionation between olivine and clinopyroxene ($\Delta_{CPX\text{-}OL} = \delta^{18}O_{CPX} - \delta^{18}O_{OL}$) is approximately 0.48‰ at 1200 °C (Zhao and Zheng, 2003). Experimentally, the difference between $\Delta_{CPX\text{-}OL}$ at 1200 °C and 900 °C is only 0.27‰. $\Delta_{CPX\text{-}OL}$ in most volcanic rocks range from approximately 0.22‰ to 0.67‰ (Anderson et al., 1971). The mafic rocks from The Pleiades have an average $\Delta_{CPX\text{-}OL}$ value of 0.29‰ (0.26–0.32‰), and the rocks of intermediate composition have an average $\Delta_{CPX\text{-}OL}$ of 0.83‰ (0.51–1.47‰) (Fig. 2b). Furthermore, the average $\Delta_{PL\text{-}OL}$ (= $\delta^{18}O_{PL} - \delta^{18}O_{OL}$) of The Pleiades rocks is 1.85‰ (1.31–2.01‰). Such high $\Delta_{PL\text{-}OL}$ values, when compared with the theoretical $\Delta_{PL\text{-}OL}$ value (~1.2‰), could be attributed to late-phase crystallization of the plagioclase from an evolved magma at a relatively low temperature (Fig. 3). Among the constituent minerals from the alkaline volcanic rocks, olivine phenocrysts provide an opportunity to study the

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Table 1. Oxygen isotope compositions, MgO contents, and Sr isotope ratios of The Pleiades volcanic rocks and basement rocks

Sample No.	Group	Rock type	$\delta^{18}O_{WR}$	$\delta^{18}O_{OL}$	$\delta^{18}O_{CPX}$	$\delta^{18}O_{PL}$	$\delta^{18}O_{melt\text{-}OL}$	$\delta^{18}O_{melt\text{-}CPX}$	$\delta^{18}O_{melt\text{-}PL}$	MgO_{WR} (wt%)	$^{87}Sr/^{86}Sr$
K16012708-4	S-M	Bas	–	4.96	5.22	–	5.78	5.56	–	7.44	0.703442
J14120107-1	S-M	Tp	–	4.81	5.13	6.54	5.63	5.53	6.40	5.20	0.703143
J14120503-2	P-M	H	–	5.22	–	–	6.03	–	–	8.39	0.703272
J14120504-4	P-I	Mu	–	5.02	5.67	7.03	5.96	6.06	6.77	4.83	0.703717
J14120106-1	P-I	Mu	–	5.36	5.87	6.67	6.30	6.27	6.41	3.42	0.704027
J14120105-1	P-I	Bn	–	4.97	5.46	6.64	5.90	6.18	6.69	1.23	0.703884
J14120103	P-I	Bn	–	4.21	5.68	6.58	5.15	6.39	6.64	1.76	0.703998
K16012709-1	P-I	Tr	–	4.46	5.50	6.48	5.40	6.21	6.53	1.64	0.703852
M16012710	P-F	Ph	–	–	5.40	6.91	–	6.46	6.83	0.57	0.703747
K16012407-2	X	Gr	8.16	–	–	–	–	–	–	2.15	0.715561
K16012422-3	X	Gr	7.18	–	–	–	–	–	–	1.95	0.715740
141215-5B	B	Mg	14.82	–	–	–	–	–	–	4.77	0.761940
141123-1A	B	GHIC	6.39	–	–	–	–	–	–	1.14	0.714313
E-1a	B	E	10.23	–	–	–	–	–	–	9.11	0.715

The precision of the laser-fluorination system based on repeated measurement of the internal obsidian is 0.10‰ (n = 13).
$\delta^{18}O_{melt\text{-}mineral}$ values are the calculated oxygen isotope composition of melt that crystallized the phenocryst, based on Zhao and Zheng (2003).
MgO contents and $^{87}Sr/^{86}Sr$ ratios of The Pleiades and basement rocks are from Kim et al. (2019a) and eclogite is from Kim et al. (2019c) and Panter et al. (2018).
Abbreviations: P: potassic, S: sodic, M: mafic, I: intermediate, F: felsic, X: xenolith, B: basement rock, Bas: basanite, Tp: tephrite, H: hawaiite, Mu: mugearite, Bn: benmoreite, Tr: trachyte, Gr: granodiorite, Mg: migmatite, GHIC: Granite Harbour Intrusive Complex, E: eclogite, WR: whole rock, OL: olivine, CPX: clinopyroxene, PL: plagioclase.

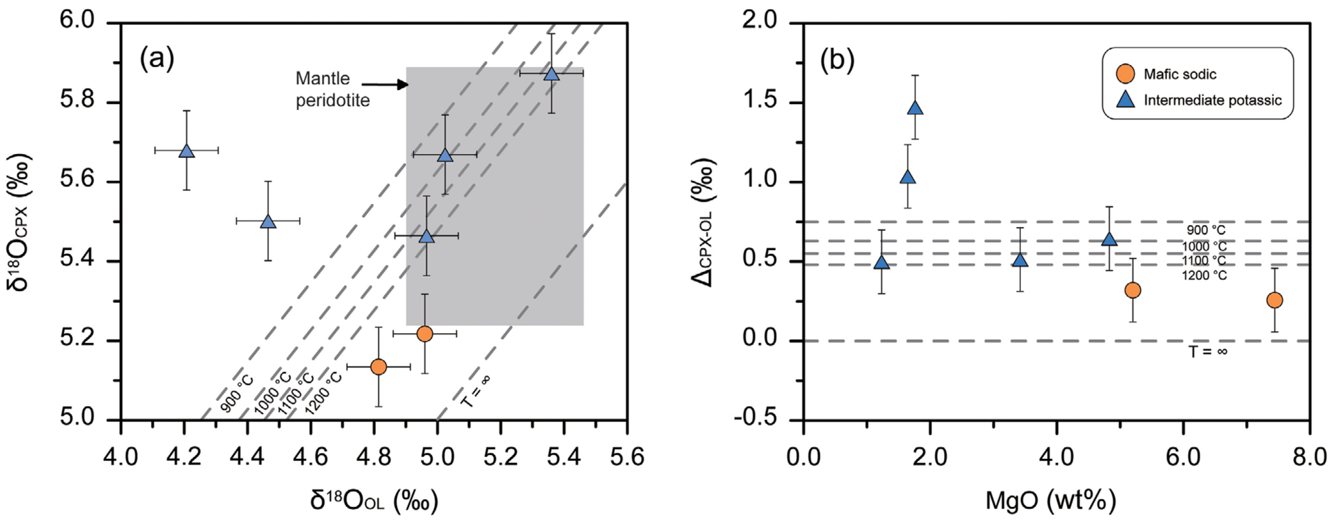

Fig. 2. Oxygen isotope compositions of olivines and clinopyroxenes. (a) Comparison of $\delta^{18}O$ of olivines and clinopyroxenes from the volcanic rocks of The Pleiades. Gray field represents the typical values for mantle peridotite (Mattey et al., 1994). (b) Oxygen isotope fractionation between olivine and clinopyroxene vs. whole-rock MgO content. Dashed lines correspond to the temperatures of oxygen isotope fractionation between olivine and clinopyroxene (Chiba et al., 1989). Error for $\delta^{18}O$ value is 1σ standard deviation assigned from repetitive analysis of the in-house reference.

characteristics of a magma during the first stages of crystallization at higher temperature and this can capture the source signatures (Eiler et al., 1997).

3.2. Temperature

Using oxygen isotope thermometry, we estimated the magmatic temperature from mineral pairs (Table 2). The calculated temperature from olivine-pyroxene pairs range from 790 to 1890 °C. Two mafic sodic samples give unrealistically high temperatures (1700 and 1890 °C). Kim et al. (2019a) estimated temperatures of ca. 1060–1230 °C for these samples using clinopyroxene-melt thermometry. Even when those two cases are excluded, the ranges of estimated temperature ($T_{OL\text{-}CPX}$ = 790–1360 °C, $T_{OL\text{-}PL}$ = 990–1320 °C, and $T_{CPX\text{-}PL}$ = 970–1300 °C) are significantly wider than the temperature range reported by Kim et al. (2019a). Although the systematic error

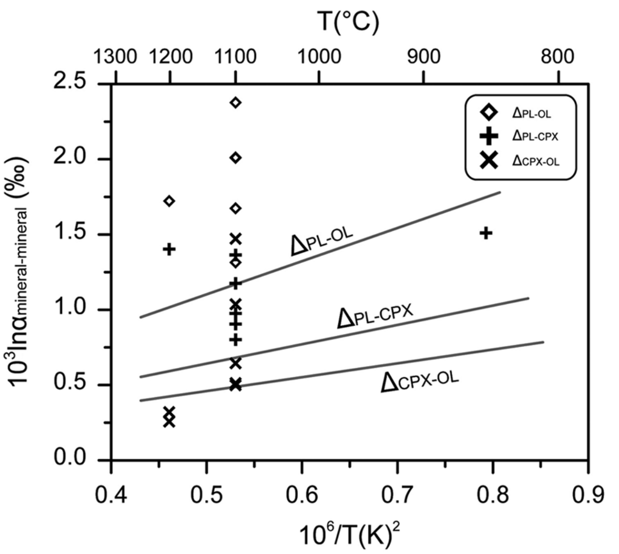

Fig. 3. Isotopic fractionation between minerals pairs of The Pleiades volcanic rocks as a function of $10^6/T^2$. For the calculation, temperatures of 1200 °C were assigned for mafic rocks, 1100 °C for intermediate, and 850 °C for felsic rocks, based on the results of clinopyroxene-melt thermometry by Kim et al. (2019a).

of temperatures estimated from oxygen isotope compositions is larger than that of temperatures determined with the clinopyroxene-liquid thermometer (Putirka, 2008), the temperatures determined from oxygen isotope compositions of mineral-mineral pairs are substantially over- and under-estimated and suggest significant oxygen isotope disequilibrium between olivine, clinopyroxene and plagioclase phenocryts within the complete range of lava compositions.

3.3. Oxygen Isotope Fractionation between Mineral and Melt

To understand the variability of oxygen isotope during magmatic differentiation, we calculated the oxygen isotope composition of the parental melt that crystallized olivine in the mafic and intermediate rocks, based on the systematic difference in $\delta^{18}O$ values between the melt (= $\delta^{18}O_{melt\text{-}OL}$) and its fractionating minerals (Eiler, 2001). An oxygen isotope fractionation between melt and coexisting minerals is expressed by the following relation: $10^3\ln\alpha_{phenocryst\text{-}melt} = A \times 10^6/T^2$, where α is the fractionation factor between two phases, T is the temperature, and A is −1.77, which is the parameter of the fractionation factor equation in the olivine-basaltic melt system (Zhao and Zheng, 2003). This equation assumes that the minerals and melts were in equilibrium and the magma represented a closed system. As shown in the equation, the oxygen isotope fractionation between the melt and mineral is correlated to $1/T^2$. The temperature of a magma decrease in accordance with its degree of magmatic differentiation, which is expressed by a decreasing trend of the MgO content or increasing trend of the SiO_2 content of the melt. Geothermometry estimates by Kim et al. (2019a) on volcanic rocks of The Pleiades estimated a higher equilibrium temperature from the mafic suites than from the intermediate suite. Thus, we assigned 1200 °C for mafic rocks and 1100 °C for intermediate rocks to calculate the oxygen isotope fractionation between olivine and melt. The calculated $\delta^{18}O_{melt\text{-}OL}$ values, ranging from 5.15‰ to 6.30‰, show a large variation when compared with the values of normal basalts at 5.8 ± 0.2‰, as shown in Figure 4 (Bindeman et al., 2004).

4. DISCUSSIONS

4.1. Oxygen Isotope Variability in Mafic Rocks of The Pleiades

The oxygen isotope composition of high-MgO mafic volcanic rocks should reflect their mantle source. Furthermore, olivine that crystallizes and differentiates early in a basaltic magma shows a narrow range and a similar oxygen isotope composition to that

Table 2. Results of oxygen isotope thermometry on mineral pairs from The Pleiades volcanic rocks

Sample No.	Group	Rock type	OL-CPX		OL-PL		CPX-PL		CPX-Liquid[(a)]
			°C	1σ	°C	1σ	°C	1σ	°C
K16012708-4	S-M	Bas	1890	100	–	–	–	–	1174
J14120107-1	S-M	Tp	1700	90	1100	30	910	40	1159
J14120503-2	P-M	H	–	–	–	–	–	–	1200
J14120504-4	P-I	Mu	1190	70	1050	30	970	40	1171
J14120106-1	P-I	Mu	1340	70	1320	30	1300	50	1102
J14120105-1	P-I	Bn	1360	70	1200	30	1120	40	1011
J14120103	P-I	Bn	790	40	990	20	1240	50	1003
K16012709-1	P-I	Tr	940	50	1050	30	1160	50	1063
M16012710	P-F	Ph	–	–	–	–	1060	40	936

The temperature estimates are based on the experimental fractionations between mineral pairs (Chiba et al., 1989).
[(a)]The temperatures are calculated using the equation 33 for clinopyxoene-liquid thermometer from Putirka (2008). The equation gives value with standard error of ±45 °C.
See Table 1 for abbreviations.

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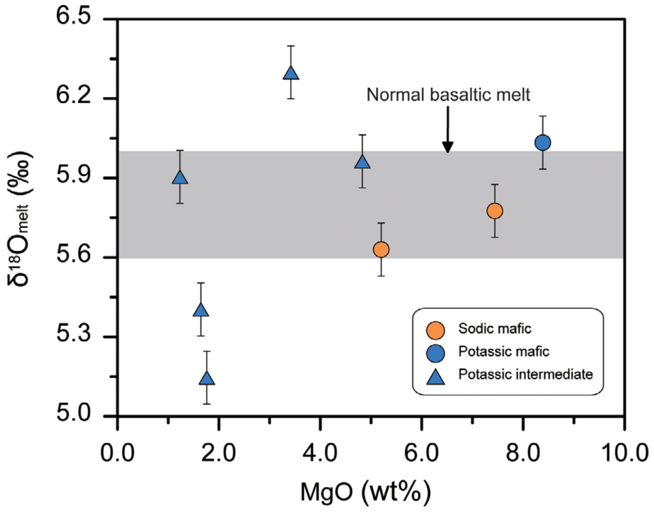

Fig. 4. Calculated oxygen isotope composition of melt from olivine ($\delta^{18}O_{melt\text{-}OL}$) vs. whole-rock MgO content. Gray area is the normal-$\delta^{18}O$ array of basaltic melt from Bindeman et al. (2004). See Figure 2 for error bars. In the potassic lineage, variation of $\delta^{18}O_{melt\text{-}OL}$ does not follow closed-system fractional crystallization. Two $\delta^{18}O_{melt\text{-}OL}$ values of the intermediate samples are unusually lower than those of normal basaltic melt.

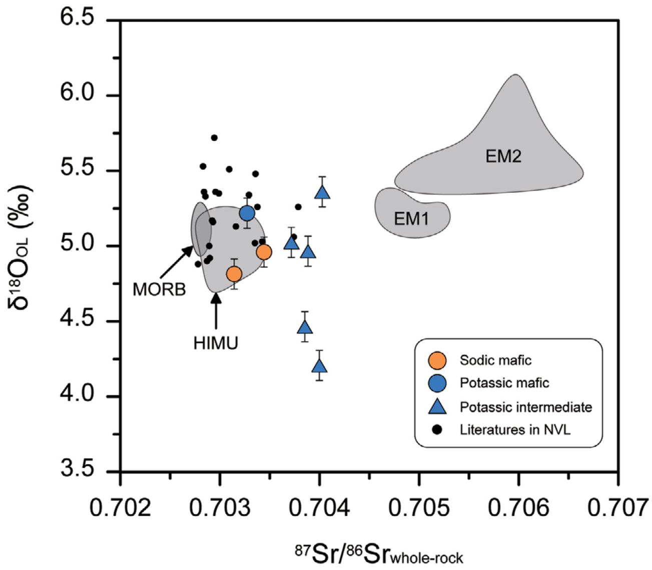

Fig. 5. $\delta^{18}O_{OL}$ vs. $^{87}Sr/^{86}Sr_{whole\text{-}rock}$ for the volcanic rocks of The Pleiades. Data for MORB, HIMU, EM1, and EM2 are from Eiler et al. (1997). Cenozoic magmatic olivines at NVL are from Nardini et al. (2009), Perinelli et al. (2011), and Panter et al. (2018). $\delta^{18}O_{OL}$ values of mafic samples overlap well with the HIMU area. Intermediate rocks of The Pleiades display more enriched Sr isotope ratios and more variable oxygen isotope compositions than the mafic samples.

of mantle olivine ($\delta^{18}O_{OL} = 5.18 \pm 0.14$‰) (Mattey et al., 1994). The HIMU basalt that is originated from mantle characterized by high U/Pb and low Rb/Sr ratios has a narrow range of oxygen isotope composition of olivine ($\delta^{18}O_{OL} = 5.03 \pm 0.11$‰) (Eiler et al., 1997). In the continental basalts of NVL (Nardini et al., 2009) and oceanic basalts of the northwestern Ross Sea (Panter et al., 2018), there is a wide span of $\delta^{18}O_{OL}$ values (4.86–5.51‰) and HIMU radiogenic isotopic signatures (Fig. 5). Panter et al. (2018) suggested that the low-$\delta^{18}O_{OL}$ values (< 5.0‰) and high $^{206}Pb/^{204}Pb$ ratio could have resulted from the melt consuming amphibole-rich veins within the metasomatized lithospheric mantle. Notably, the oxygen isotopes in olivine from hawaiite (J14120503-2) of the potassic lineage overlaps with the mantle array, but the oxygen isotope values measured on olivines from basanite (K16012708-4) and tephrite (J14120107-1) of the sodic lineage are lower than that of the potassic lineage (Fig. 5). Furthermore, the unreasonable temperatures calculated from olivine and pyroxene pairs of the sodic mafic rocks indicate that oxygen isotope composition of magma crystallized the minerals was modified relative to normal mantle. The temperatures calculated from clinopyroxene-liquid thermometer in the mafic samples show significantly lower temperatures than the results of oxygen isotope thermometry (Table 2). The temperatures calculated based on the oxygen isotopes show the oxygen isotope disequilibrium in the minerals of The Pleiades. Kim et al. (2019a) demonstrated that the volcanic rocks of the two distinctive fractionation lineages of The Pleiades were derived from a similar amphibole bearing metasomatized lithospheric mantle. The primary melt of The Pleiades could have evolved to the potassic lineage magma via sufficient reaction with the surrounding peridotite, whereas the sodic lineage magma would be less affected by the reaction between the melt and peridotite. Perinelli et al. (2011) reported that $\delta^{18}O_{OL}$ in an amphibole-bearing sample was the lowest among the mantle cumulate xenoliths. Thus, we suggest that the oxygen isotope variation of The Pleiades may have resulted from the varying degree of reaction between a melt consuming a low-$\delta^{18}O$ amphibole vein and the surrounding mantle peridotite.

4.2. The Effects of Assimilation and Fractional Crystallization

Variations in the oxygen isotope composition of volcanic rocks can be used to assess the effect of fractional crystallization (Taylor and Epstein, 1962). Studies on oxygen isotopes, investigating the effect of fractional crystallization on volcanic rocks, have shown that the $\delta^{18}O$ values increase by roughly 1‰ when crystallization is more than 80% (Woodhead et al., 1987; Harris et al., 2000; Bucholz et al., 2017). Modeling studies have also suggested that an increase in $\delta^{18}O_{melt}$ is limited within 1‰ over the series of crystallization processes (Eiler, 2001; Bindeman et al., 2004). In the potassic lineage, the intermediate rocks show anomalously modified $\delta^{18}O_{melt\text{-}OL}$ values (Fig. 4). The $\Delta_{CPX\text{-}OL}$, $\Delta_{PL\text{-}CPX}$, and $\Delta_{PL\text{-}OL}$ fractionation values indicate disequilibrium conditions, as do the results of temperature calculations (Fig. 3). Two $\Delta_{CPX\text{-}OL}$

values of the mafic sodic lineage plot below the equilibrium line. Two $\Delta_{OL\text{-}CPX}$ values of intermediate potassic lineage plot on the line, while the other three values are larger than the values indicated by the equilibrium line. It is noted that the high $\Delta_{CPX\text{-}OL}$ values of two benmoreites (J14120105-1 and J14120103) were caused by low-$\delta^{18}O$ olivines. All $\Delta_{PL\text{-}CPX}$ and $\Delta_{PL\text{-}OL}$ values are higher than those exhibiting equilibrium conditions. The oxygen isotope compositions of mafic to felsic lithologies of the potassic lineage may be related to the complex fractional crystallization effect.

The low-$\delta^{18}O$ characteristic can be elucidated by possible processes: (1) hydrothermal alteration caused by meteoric water (Gregory and Taylor, 1981; Kawahata et al., 2001), (2) partial melting of hydrothermally altered material (Bindeman and Valley, 2000; Zheng et al., 2004), and (3) assimilation of hydrothermally altered material (Widom and Farquhar, 2003; Genske et al., 2013). Oxygen isotope composition of meteoric precipitation sampled in the NVL is about −20‰ (French and Guglielmin, 2000). The hydrothermal circulation of low-$\delta^{18}O$ water is considered through a crustal fracture developed by mantle upwelling. However, the P-T conditions estimated from clinopyroxene phenocrysts of The Pleiades indicate that the crystallization depth for olivine in The Pleiades volcanic rocks could be as deep as the Moho depth (6.9–12.0 kbar and 850–1230 °C, table 4 in Kim et al., 2019a). This implies that olivine phenocrysts in the mafic rocks at NVL were crystallized in the lowermost crust and it is difficult to affect oxygen isotope composition of deep-seated magma by direct infiltration of meteoric water. Partial melting of hydrothermally altered material is another possible process that can produce low-$\delta^{18}O$ melt. The possibility exists that the hydrothermally altered low-$\delta^{18}O$ material subducted into lithospheric mantle during Ross orogeny (Rocchi et al., 2011). However, geochemical studies suggest that the Cenozoic volcanic rocks including The Pleiades in NVL are result of a partial melting of metasomatized lithospheric mantle (Nardini et al., 2009; Panter et al., 2018; Kim et al., 2019a).

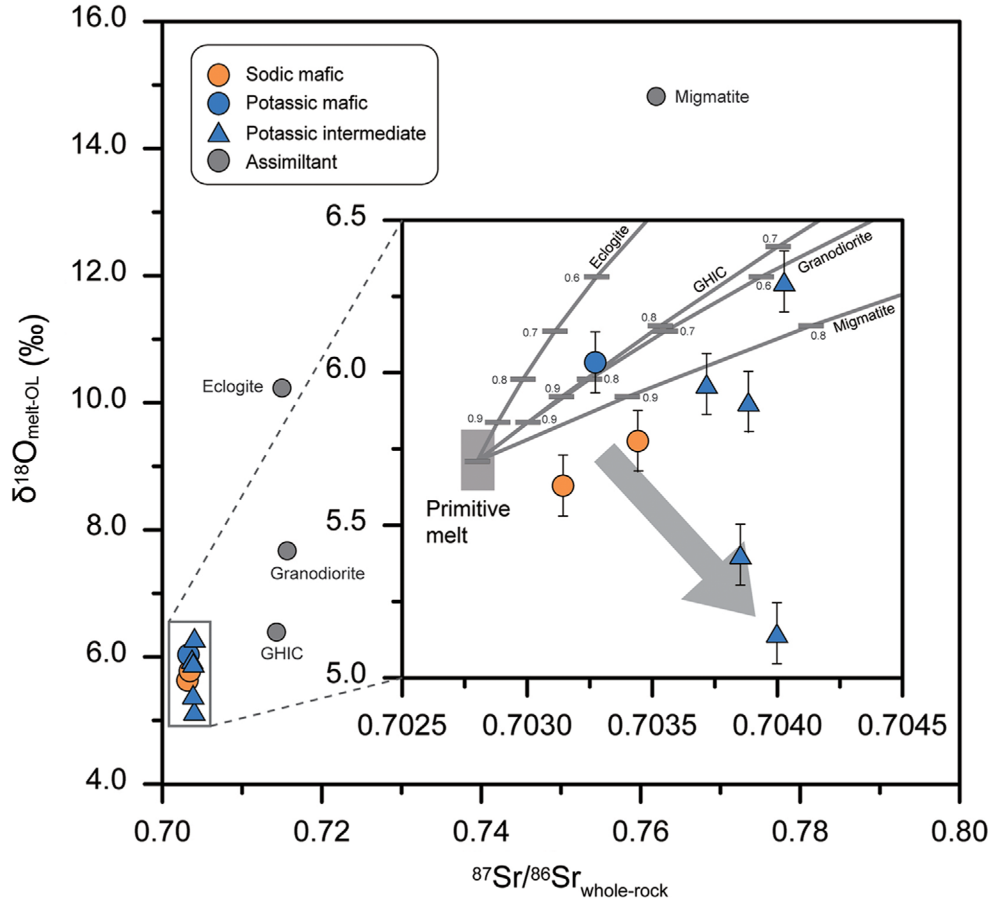

Fig. 6. Assimilation and fractional crystallization (AFC) modeling for $\delta^{18}O_{melt}$ vs. $^{87}Sr/^{86}Sr_{whole\text{-}rock}$ using the equation of DePaolo (1981). For the calculation, we assumed that the partition coefficient for Sr = 1.83 (Rollinson, 2014). Initial $\delta^{18}O$, $^{87}Sr/^{86}Sr$, and Sr concentration of primitive melt are 5.71‰, 0.7028, and 145 ppm, respectively (Ito et al., 1987; Sun and McDonough, 1989). Crustal rocks are granodiorite, migmatite, and granite (Kim et al., 2019a) and eclogite (Di Vincenzo et al., 2016; Panter et al., 2018). Bar marks indicate the fraction of liquid remaining (each mark represents 10%). A mass ratio of assimilated to crystallized material of 0.1 was used for the calculations. Thick gray lines indicate AFC modeling for basement rocks and eclogite found in NVL. Gray arrow indicates the approximate trend of decreasing $\delta^{18}O_{melt}$ and increasing $^{87}Sr/^{86}Sr$ ratio.

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The lithospheric mantle beneath NVL has a normal mantle oxygen isotope composition of 5.37 ± 0.27‰ (Perinelli et al., 2006) which suggests that the parental magma for The Pleiades was modified by some process such as assimilation. We measured the oxygen isotope compositions of basement rocks in NVL to examine them as possible candidates for contamination that may have affected the oxygen isotope composition of the magmas (Table 1). The calculated $\delta^{18}O_{melt}$ values of olivine, the Sr isotope compositions, and the assimilation and fractional crystallization (AFC) trends of basement rocks are illustrated in Figure 6. Depending on the AFC modeling, the basement rocks, granodiorite, migmatite, and GHIC are possible assimilants that could have increased the $\delta^{18}O$ value and Sr isotopic ratio of the melt. The results of AFC modeling show that three samples (J13120503-2, J14120504-4, and J14120106-1) plot along the AFC trend calculated from the basement rocks. Although one sample (J14120105-1) plot slightly off from the trend, it is also likely that the sample was contributed by assimilation of basement rock. However, to explain low-$\delta^{18}O$ of two intermediate volcanic rocks (J14120103 and K16012709-1) by AFC process, the assimilant would have significantly low oxygen isotope composition. The granulite facies metamorphic rocks exposed in NVL may constitute the continental lower crust and could be sources of the Paleozoic granites in NVL (Borg and DePaolo, 1991; Dallai et al., 2003). The oxygen isotope compositions of granulite xenolith samples, regarded as a part of lower continental crust, range from 3.8 to 10.5‰ (Dobosi et al., 2003). The assimilation of granulite could have increased the oxygen isotope composition of The Pleiades magma during its magmatic evolution. However, it is still unclear whether the granulite controls the decreasing trend of $\delta^{18}O_{melt}$. As an alternative explanation of the petrogenesis of Cenozoic NVL volcanic rocks, it has been suggested that recycled eclogite could remain in the lithosphere (Di Vincenzo et al., 1997; Melchiorre et al., 2011). Eclogite formed by underthrusting of the oceanic crust may exist beneath the continental crust at the continental boundary (Helmstaedt and Gurney, 1995; Griffin and O'Reilly, 2007). The NVL province experienced subduction and orogenic processes during the early Paleozoic. The eclogite found at NVL records a minimum pressure of 15 kbar in its constituent minerals (Di Vincenzo et al., 1997; Rocchi et al., 2011, 2016). Furthermore, Lu-Hf and Re-Os isotopic studies of mantle xenoliths from NVL suggest that radiogenic Hf and Os isotopic compositions in the samples exhibit the effects of recycled eclogitic materials (Melchiorre et al., 2011). Mafic eclogite can have an extreme range of oxygen isotope compositions, from –10.9 to +8.5‰ (Zheng et al., 1998, 2004). The extremely low oxygen isotope composition of eclogite may be caused by the exchange between low-$\delta^{18}O$ water and rock over a wide range of temperatures, pressures, and water/rock ratios. For these reasons, we measured the oxygen isotope composition of eclogite found in the Lanterman Range to examine the possibility of low-$\delta^{18}O$ material beneath NVL. Against our expectation, the eclogite was enriched in $\delta^{18}O$ (10.23‰, Table 1). While the AFC modeling does not confirm a low-$\delta^{18}O$ candidate, we cannot simply rule out a probability of low-$\delta^{18}O$ existing. Troch et al. (2020) recently reviewed the low-$\delta^{18}O$ silicic rocks that were originated from hydrothermally altered rocks worldwide. The low-$\delta^{18}O$ silicic rocks are can be generated by assimilation or partial melting of hydrothermally altered rocks. The wide variation of oxygen isotope composition of The Pleiades might be evidence for contribution of the low-$\delta^{18}O$ silicic rocks or earlier hydrothermally altered material during magmatic evolution.

5. CONCLUSIONS

(1) The oxygen isotope compositions of mineral separated from The Pleiades volcanic complex in NVL range from 4.21‰ to 5.36‰ for $\delta^{18}O_{OL}$, 5.13‰ to 5.87‰ for $\delta^{18}O_{CPX}$, and 6.48‰ to 7.03‰ for $\delta^{18}O_{PL}$.

(2) The $\delta^{18}O_{melt\text{-}OL}$ values represent a wide range of oxygen compositions that deviate from that of the normal-mantle array. According to the $\delta^{18}O_{OL}$ values of mafic rocks, the melt of The Pleiades could have originated from the low-$\delta^{18}O$ amphibole-bearing metasomatized lithospheric mantle. Subsequently, the melt of potassic lineage, which reacted sufficiently with surrounding mantle peridotite, crystallized olivine with a mantle-like oxygen isotope composition. The sodic lineage, however, interacted much less with the anhydrous peridotite and then crystallized olivine with a low-$\delta^{18}O$ value inherited from the signature of the metasome.

(3) The relationship between $\delta^{18}O_{melt\text{-}OL}$ and the $^{87}Sr/^{86}Sr$ ratio indices in the volcanic rocks of The Pleiades suggests that at some point in its evolution, the magma of The Pleiades assimilated unusually low-$\delta^{18}O$ material from the lower crust.

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